

SOME USEFUL INNOVATIONS WITH TRASYS AND SINDA-85

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SUMMARY

Several innovative methods have been used to allow more efficient and accurate thermal analysis using SINDA-85 and TRASYS, including model integration and reduction, planetary surface calculations, and model animation. Integration with other modeling and analysis codes allows an analyst to import a geometry from a solid modeling or computer-aided design (CAD) software package, rather than building the geometry "by hand." This is more efficient as well as potentially more accurate. However, the use of solid modeling software often generates large analytical models. The problem of reducing large models has been elegantly solved using the response of the transient derivative to a forcing step function.

The thermal analysis of a lunar rover implemented two unusual features of the TRASYS/SINDA system. A little-known TRASYS routine SURFP calculates the solar heating of a rover on the lunar surface for several different rover positions and orientations. This is used not only to determine the rover temperatures, but also to automatically determine the power generated by the solar arrays. The animation of transient thermal results is an effective tool, especially in a vivid case such as the 14-day progress of the sun over the lunar rover. An animated color map on the solid model displays the progression of temperatures.

INTRODUCTION

In many industries there has recently been a concerted movement toward "quality management" and the issue of how to accomplish work more efficiently. Part of this effort is focused on concurrent engineering: the idea of integrating the design and analysis processes so that they are not separate, sequential processes (often involving design rework due to analytical findings) but instead form an integrated system with smooth transfers of information. Specific examples of concurrent engineering methods being carried out at NASA Langley Research Center (LaRC) are: integration of thermal, structural and optical analyses to predict changes in optical performance based on thermal and structural effects; integration of the CAD design process with thermal and structural analyses; and integration of thermal analysis with animation to show the thermal response of a system as an active color map -- a highly effective visual indication of heat flow.

Electronic integration of design and analysis processes was achieved and refined during the development of an optical bench for a laser-based aerospace experiment. One of the driving requirements for any complex optical system is its alignment stability under all conditions. Accurate predictions of optical bench or test bed deflections are necessary to calculate beam paths and determine optical performance. Another requirement that is increasingly demanded of any analysis process is to do it faster and better; create a more streamlined process and include all known variables to produce the best possible predictions. These goals can be accomplished by using an integrated process to accomplish design and all analyses. This integrated analysis process has been built around software that was already in use by designers and analysts at LaRC. The PATRAN[®] solid modeling / finite element package is central to this process, since it was already in common use at LaRC. Most of the integration and interface steps described here are also

possible with other packages, although certain of the translators were developed or modified for use with these specific software packages.

Modeling with any solid geometry package, such as PATRAN, tends to encourage the use of larger models than a thermal analyst would tend to produce. Since the geometry is more accurate, it has more complexity and requires finer nodalization. Also, the meshing capability allows quick, automatic generation of models with more nodes than would be generated by hand. These larger models must be reduced to produce the type of model required for a space-flight experiment. One way this has been done at LaRC is to compare the derivative of the transient thermal response to a forcing step function, and correlate this response with the transient response of a smaller model.

In the analysis of a lunar rover, a subroutine in TRASYS called SURFP was used for the first time at LaRC. This routine calculates the solar and IR heating for a spacecraft that is stationary on the planetary surface. By evaluating heating at several different positions on the lunar surface over a lunar day, the entire thermal environment for a traversing rover can be calculated. Also, the solar flux values were used to calculate the power levels generated by the rover's solar arrays, and thus determine what level of charge the battery would achieve.

The process of thermal animation, which is a natural outgrowth of model integration with the solid modeling codes that have this built-in capability, is especially effective for a situation such as the lunar rover, where the angle of the sun to the vehicle is constantly changing.

The efforts of Kelly Smith and Jill Marlowe in structural analysis, Steve Hughes and Al Porter in design, Maria Mitchum in software development, and Greg Herman and Alan Little in optical analysis are gratefully acknowledged.

ANALYSIS INTEGRATION

The heart of the concurrent engineering process described here is the use of a single integrated model for thermal and structural analysis of a system. This allows a savings of time in the thermal and structural analysis work, since only one geometric model must be developed. It facilitates electronic transfer of data between all types of analysis, such as transfer of exact thermal gradients to be used in structural analysis. Finally, it produces greater model accuracy since the model can be directly imported from the design software package.

Interfaces between Analysis and Design Software

The design software most often used in this process at LaRC is Pro-Engineer®. A part is completely designed in Pro-Engineer, which produces a three-dimensional model of the part as well as all the fabrication drawings. A Pro-Engineer solid shaded model of a complex assembly is shown in Figure 1. This example assembly is a laser reference cavity which is mounted on an optical bench. There are three basic methods available to translate from Pro-Engineer CAD software to the PATRAN solid modeling software. All these methods have been used to produce viable models. One is to mesh the solid geometry of the part in Pro-Engineer and translate that mesh to PATRAN. The disadvantages to this method are: only the mesh is transferred, not the underlying solid geometry, so the geometry and mesh cannot be changed in PATRAN; and the mesh is limited to only tetrahedral or triangular elements. The second method is to transfer the part from Pro-Engineer to an IGES file, which is a standard graphics format, and read this file into PATRAN using the CADPAT translator. This translates the phase I (underlying) geometry, but only in the form of surfaces and lines, not PATRAN's solid geometry elements called hyperpatches. Thus the analyst must still define hyperpatches based on the geometry described by the translated surfaces. This can be helpful as the analyst can choose to ignore details such as bolt holes in constructing the analytical model. The disadvantages to this method are the rework in creating the solid form from the transferred

surfaces (which only applies when the part being transferred is a solid rather than plate elements), and that during translation of an assembly of parts, the orientation of the individual parts is lost and the assembly must be reconstructed from the components. The third method is to bring the solid geometry from Pro-Engineer directly into PATRAN. This method is only viable for the newer releases of both Pro-Engineer (Version 10 or later) and PATRAN (3.0). The solid geometry can then be either directly meshed, or used to create hyperpatches. An example component of the laser reference cavity is shown as an IGES file (Figure 2) and as completed with elements (Figure 3). Parts have also been brought into PATRAN from ANVIL, but this brings across only the 2-D shape and position of parts.

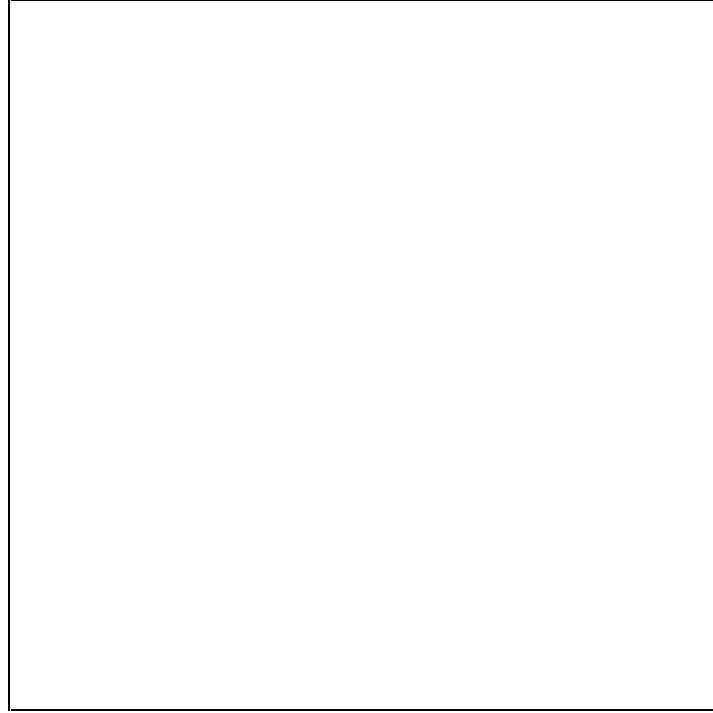


Figure 1. Laser reference cavity as designed and portrayed in Pro-Engineer

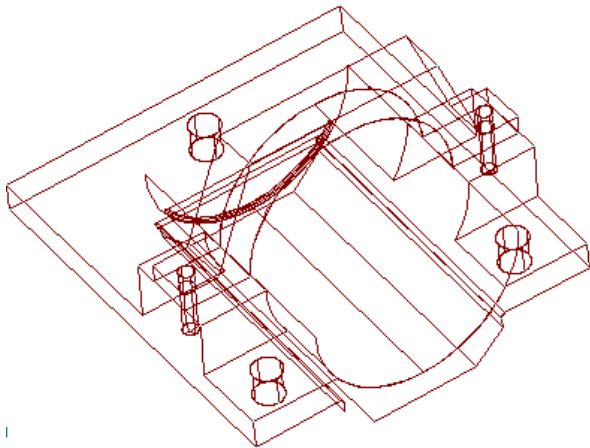


Figure 2. Mount surfaces imported to PATRAN from ProEngineer through IGES file

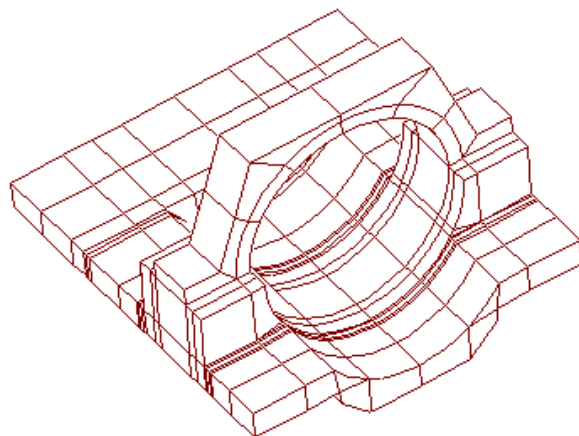


Figure 3. Mount part with solid elements created in PATRAN

The integration of design and analysis has several benefits. In terms of streamlining the process, there is much less work to be done by the analyst since the majority of the geometry is imported automatically. The entire process of taking dimensions from a design drawing and manually building up the geometry is eliminated. Also, the analyst is automatically working with the most current version of the design. Eliminating the repeated step of entering the dimensions lessens the probability of errors in the model. Geometries that are difficult to model and would perhaps be approximated are automatically translated exactly.

Interface between Thermal and Structural Analysis

The translators between structural and thermal analytical models are already built into the PATRAN system. The analysts can easily use the same geometric model, perform analyses through their separate software packages, and share the results electronically. There are a few techniques that make this type of translation easier and more effective. The model can be built in PATRAN by either analyst, but there must be communication between the analysts before the model is built, so that the final model will have a structure and level of detail appropriate for both analyses. One unique aspect of the work described herein is that the structural and thermal analysts determined together what method would be best for both of them in modeling certain parts, before the model was developed. A requirement on the thermal side that must be maintained in the model in order for it to be useful for the thermal analyst, is that between every pair of connected elements all corner nodes must be identical. Also, the best translation to a thermal model is currently achieved by using solid elements rather than plate elements in most cases. Many of the connections between solids and plates and plates-to-plates, that are correct for structural analysis, do not work correctly for thermal analysis. In order for each analyst to be able to easily create their own mesh, or use the same mesh, the phase I geometry must meet the requirements of both analysts.

The only change that must be made to alter the model between use by the thermal and structural analysts is a re-definition of the material properties, usually a five to ten minute task. The material identification is maintained through the transfer; only the actual material properties need be input again. Unfortunately the material properties are exclusive, so that each time the PATRAN model is transferred between analysts, the material properties must be redefined. Normally, the transfer is done only once. Improvements slated for PATRAN 3.0 will do away with this concern.

To perform the thermal analysis, the PATRAN model is translated to SINDA-85, a finite difference thermal analyzer, using the PATSIN translator¹. This SINDA-85 model is used to perform thermal analysis, with some modifications such as adding power sources. The structural analysis can be performed in P/FEA² (a software package that directly interfaces with PATRAN) or after translation to NASTRAN³. The analysts sometimes desire different levels of detail; thermal analysis commonly uses a lower level of detail than structural analysis. In that case, an identical PATRAN phase I geometry of patches and hyper-patches is still used; each analyst can create their own mesh. The calculated temperatures can be used to impose accurate thermal loads on the structural model regardless of whether the meshing is the same, as long as the phase I geometry is identical. This has been checked using two different meshings and element numbering schemes on a model; the interpolated values were found to be correct.

One way to use the nodes and conductors created by PATSIN is to separate them into files that are called into the SINDA model using an INCLUDE statement. Thus the SINDA model can contain other data such as heating arrays; if there is a change to the PATRAN model it will only affect the included files, with the main SINDA model left unchanged. The output of PATSIN is often quite bulky, which would make editing of the full SINDA model more difficult. Using included files limits the size of the SINDA model file, and allows several different SINDA files to reference the same PATRAN model.

The thermal results, either from a steady state analysis or from time steps in a transient run, are translated by SINPAT to produce element and nodal temperature files that can be read by PATRAN. These files can be read directly into PATRAN, and the thermal results mapped onto the model geometry.

One advantage to the integrated method is the capability for viewing temperatures that are mapped back onto the geometry of the part. This provides a concrete display which can be used for demonstration of effects, or for de-bugging the model. Some examples of the effectiveness of this display are shown in Figures 4, 5, and 6. In Figure 4, thermal mapping on a laser reference cavity is shown. In this case, it was desirable to have a detailed model and direct transfer of temperatures since the structural analysis was required to predict displacements down to the micron level. In Figure 5, the PATRAN model was created by a designer for display only, and used for thermal mapping to visually verify the position of the rover with respect to the sun. In Figure 6, a cryocooler support bracket and its mounting scheme to a cold bus is portrayed. In this case, the internal heating of the cryocooler is critically dependent on the geometry of the mounting system, so the exact part geometry was imported from Pro-Engineer and used to perform both the thermal and structural analyses.

To use the nodal temperatures as actual thermal loads rather than only for display, the files must be run through a program called READER that translates the files to binary format. The results can be interpolated onto the structural model using a built-in utility of PATRAN (TEMP, ADD/INT)⁴. The thermal results, imported into the PATRAN model, can be used in the structural analysis software to calculate thermally driven stresses and deflections based on the predicted temperature distribution. These thermal stresses can be summed with any load-driven stresses, to produce a total reaction of the system to the environmental constraints.

Exporting Thermal Results to Optical Analysis

Most optical models start with the assumption that the system is aligned and at rest. The optical analyst inputs surfaces, sources and objects at their designed location, and determines the performance of the system. The optical code currently used by many analysts at LaRC is CODE-V[®]. During actual operation of the optical system, there will often be factors that cause distortions to the aligned system. In the case of an optical bench with optical components mounted on it, there can be thermal gradients across the bench that will cause minute warping of the bench and result in significant distortion of the optical system from its baseline aligned performance. There can also be structural loads imposed which cause deflections, and both the thermal and mechanical loading environments can be changing with time. There is an existing translator that will look at the deformation of a single optical element such as a lens in NASTRAN, and translate the appropriate information to CODE-V to determine the distorted lens performance. However, for the optical bench structure, a method was needed to look at changes in the overall performance based on distortions of the entire bench, not only a single element.

To accomplish this, an output file of nodal deflections is generated by the structural analysis software, with six values for each optical surface (rotations and translations in each of three axes). The deflections can be due to thermal, structural or any combination of loading conditions. A relational file is developed for that model that relates the nodes in the PATRAN model to the optical surfaces in the CODE-V model. Translation software (PATCODV) was developed at LaRC to read the structural analysis deflection file, the relational file, and a copy of the undeflected CODE-V model. It produces a new CODE-V model that has new positions and angles for the optical elements based on summing the predicted deflections and the original positions of the elements. CODE-V can then be run on the new model, and optical performance based on the distorted system is predicted. For any optical system there is usually only one PATRAN model, but there can be a separate CODE-V model for each optical path. The translation must be run for each optical path for which deflection analysis is desired. The translation can be run for a series of time steps, using deflection results files for each time step, to predict the performance of the system as a function of time. Figure 7 demonstrates the steps of this process pictorially by showing: (a) a map of the thermally driven distortions from this distribution; (b) a map of distortions due to structural loading; and (c) and a map of the combined distortions. Development of a user's manual for this translation software is currently underway at LaRC.

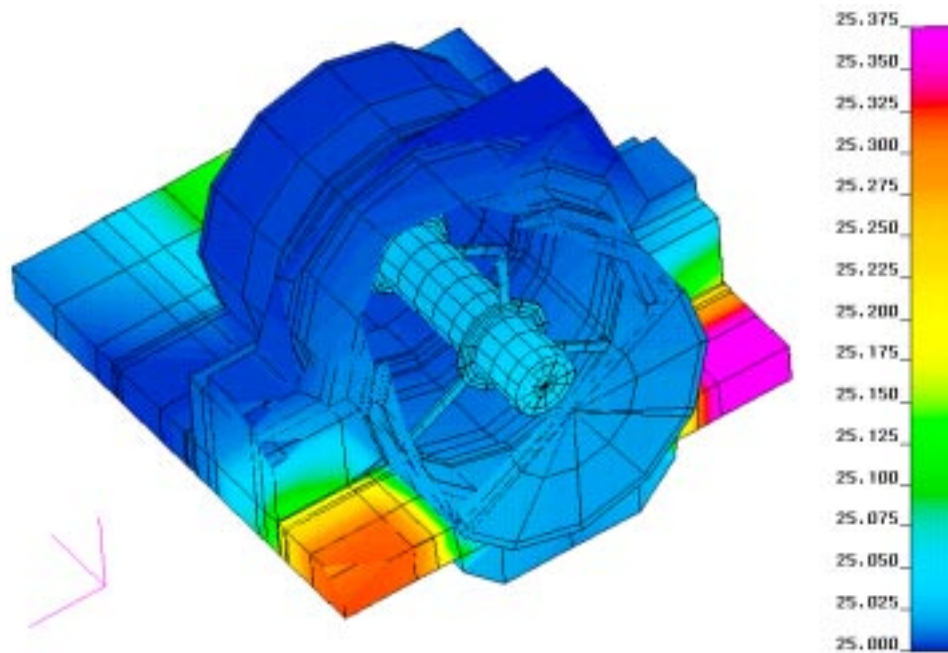


Figure 4. Laser Reference Cavity Thermal Mapping

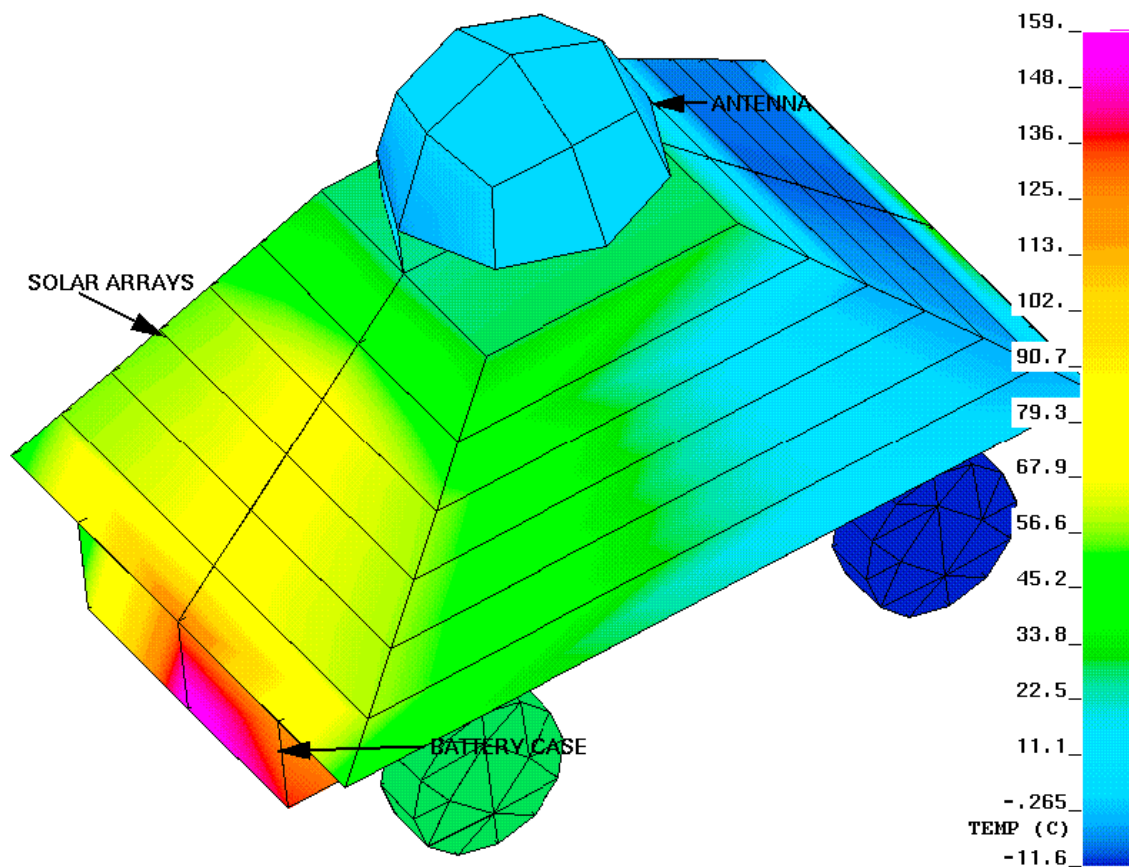


Figure 5. Lunar Rover Thermal Mapping

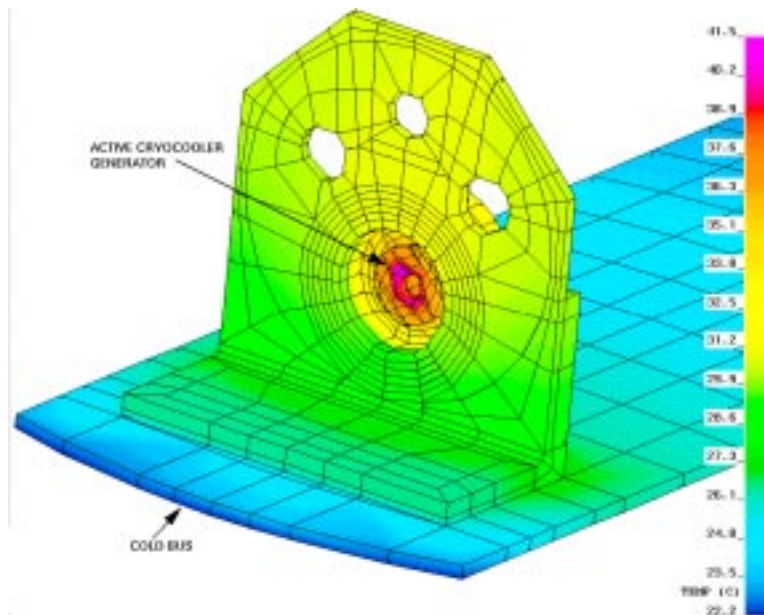
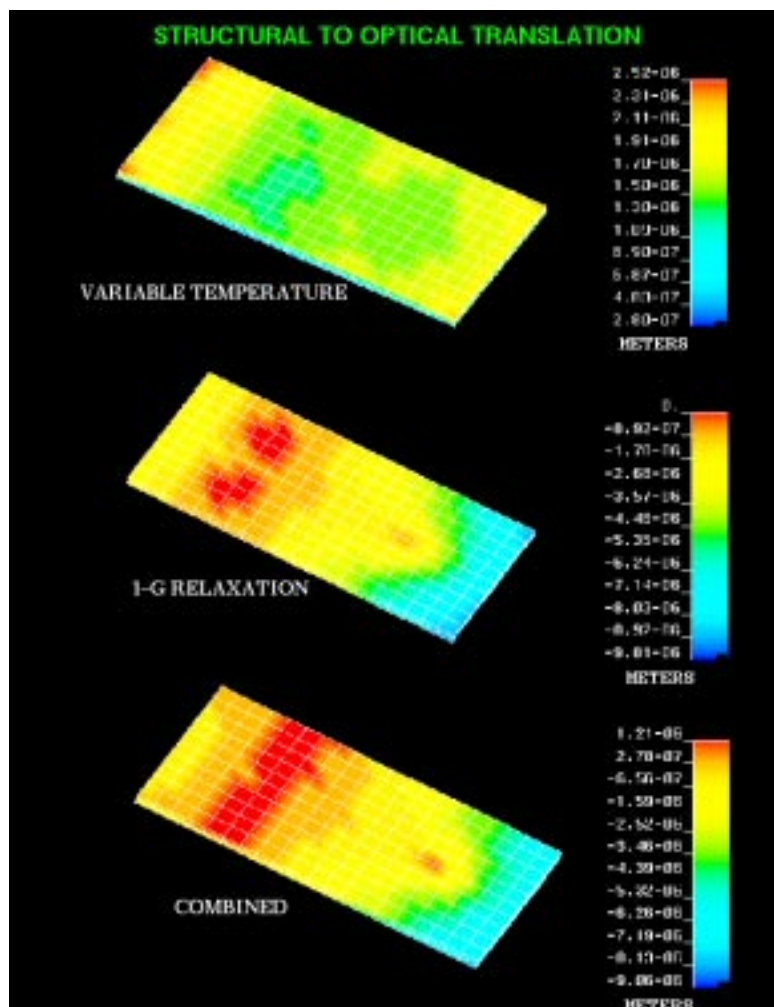


Figure 6. Cryocooler Mounting Bracket Thermal Mapping



THERMAL CORRELATION USING TRANSIENT

The large thermal models that are developed by using a solid modeling code can be intimidating in size, and can also be unwieldy to correlate with test results. Another disadvantage to the size has to do with the standard procedure for thermal analysis of a space-flight instrument. Normally, a reduced (10 to 12 node) thermal model of an instrument would be delivered to the flight carrier, so that an integrated spacecraft model can be run using all the instrument reduced models. The models developed from PATRAN are too large to be delivered, and they cannot be easily reduced to the required size since they were not developed from hand calculations. The method used here for this model reduction is evaluation of the transient derivative behavior. Key nodes in the model, which are appropriate to be lumped-mass nodes of a reduced model, are selected. The response of those nodes to a forcing step function at an active boundary is evaluated. The best response to evaluate is the derivative of the transient response. In other words, instead of plotting the temperature change of a node, one plots the temperature change per unit time. This leads to a much clearer demonstration of the behavior of the model. The transient derivative response is also useful in correlating models to test data.

Two examples of this method are shown. First, the thermal response of a laser reference cavity that is insulated from the environment is shown in Figure 8. Thermal test data and the predicted data from a large model are plotted; in both cases the same boundary temperature was ramped. It is difficult, from this plot, to evaluate the changes that must be made to the model to correlate it with the test data. In Figure 9, however, the derivative of the transient response is shown. From this plot it is possible to evaluate the exact difference in time and magnitude shown by the transient behavior. The response time of the model lags the test by about 20 minutes (indicating thermal masses that are somewhat too high), and also predicts too low a magnitude for the maximum transient derivative (indicating that the conductances should be increased slightly).

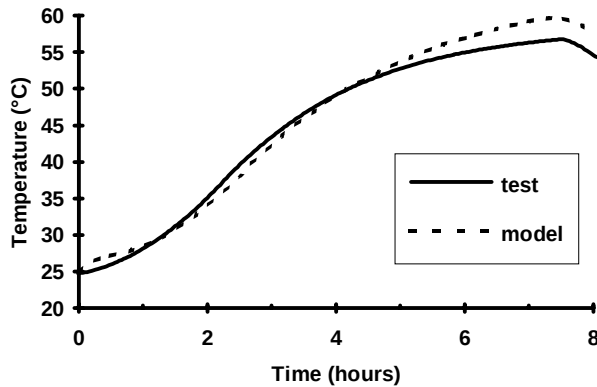


Figure 8. Comparison of Test and Prediction for Thermal Transient

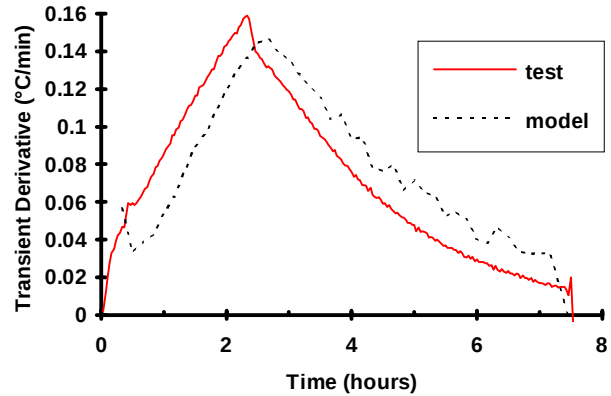


Figure 9. Comparison of Test and Prediction for Thermal Transient Derivative

The second example uses a model of a similar laser cavity placed on an optical bench within a spacecraft. The entire model contained about 3000 nodes. In order to perform an analysis of the noise frequencies of the cavity and their dependence on the orbital period, it was desired to reduce the model to five nodes while still accurately representing the cavity behavior. Nodes were chosen to represent the spacecraft, mounting plate, optical bench, cavity mount, and cavity. The spacecraft temperature was used as the forcing step function. The transient derivative was plotted for the full model, and for an approximate guess of the reduced model. By evaluating the differences, the reduced model predictions were brought into agreement with the full model predictions, as shown in Figure 10. The behavior of the cavity in the five node model could then be described with a single equation.

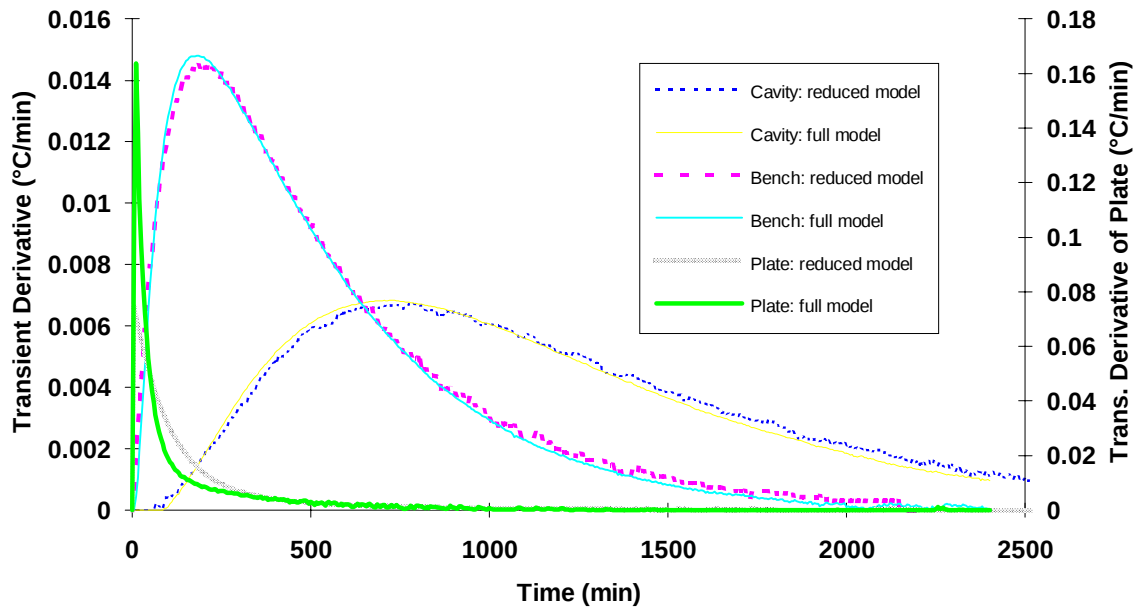


Figure 10. Comparison of Predicted Transient Derivative for Full and Reduced Models

LUNAR SURFACE RADIATION CALCULATIONS

A thermal model was developed for a lunar rover that was designed to be mobile on the surface of the moon. Solar flux radiation calculations in TRASYS had not been previously performed for a spacecraft on the surface of a planet (at least at LaRC). A subroutine in TRASYS called SURFP is available for this type of calculation⁵. In SURFP the user defines the planet, the position on the planet surface, the time of year, and any atmospheric extinction. Table 1 shows the actual code used in the operations data block, after calculation of the radiation conductors.

Table 1. TRASYS Subroutine SURFP Implementation

```

C  ORBITAL DEFINITION USING ROVER ON SURFACE OF PLANET
CALL SURFP ('MOO',45.,0.,0.)          $ Define position
CALL DICOMP (0,IZERO,IZERO)
CALL AQDATA('ZERO','1.,1.,1.,')      $ Define format for printout
AQPRNT='YES'
CALL QODATA(0,100,'YES','929.,3.1546E-4, 1., 'BOTH','')
STEP 10000                            $ Start orbit
    TIMEPR = DAWN                      $ Define each orbit step
desired
L   DICAL
L   AQCAL
...step thru each orbit position...
STEP 10011
    TIMEPR = DUSK+12
L   DICAL
L   AQCAL
L   QOCAL                            $ Print flux tables

```

A quirk to this subroutine is that only direct solar fluxes to the spacecraft surfaces are automatically computed. To compute infrared (IR) and planetary albedo fluxes, a ground plane with sufficient size and appropriate properties must be constructed to simulate the planet surface. The nodalization of this ground plane surface should be carefully evaluated to ensure it is not distorting the results.

The lunar rover model, plotted in TRAVIEW⁶, is shown in Figure 11. The solar fluxes calculated by TRASYS were spot-checked with hand calculations to ensure that the subroutine was being operated correctly. The computed heat fluxes as a function of time over a lunar day cycle were used to calculate the temperatures of the rover over time. The temperature variation over parts of the rover during a lunar day is shown in Figure 12. The radiation calculations were performed for several different rover orientations and positions on the lunar surface.

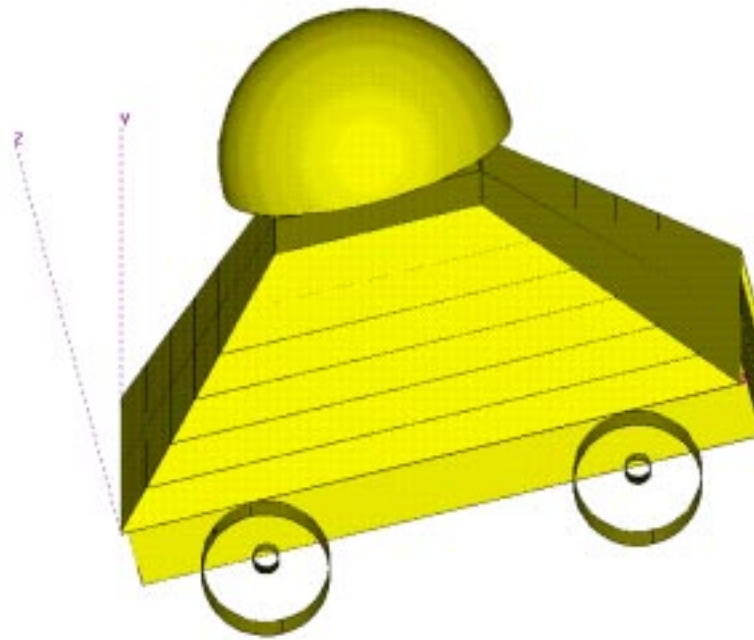


Figure 11. TRASYS Model of Lunar Rover

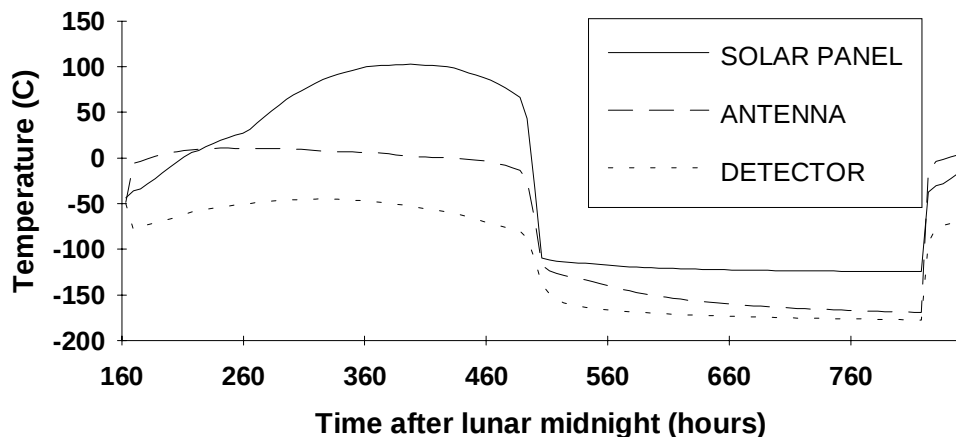


Figure 12. Temperature Variation on Selected Components over Lunar Day

SOLAR ARRAY POWER CALCULATIONS

The solar flux arrays generated by TRASYS were used for more than temperature calculations in SINDA. A key concern in the rover design was correct sizing of the solar arrays and batteries. Before the thermal model was developed, power output of the solar arrays was estimated roughly using a constant temperature for the array material, and approximations for solar flux on the rover geometry. With the combined TRASYS / SINDA model, the solar array power calculation could be done exactly. The solar heating array from TRASYS is included in the SINDA logic block⁷. Instantaneous incident power is calculated at each time step by interpolating the absorbed solar heating for each surface, multiplying by the area fraction that is effective solar array material, and dividing by the absorptivity. The photoelectric efficiency of the material is calculated in SINDA, based on the equation given by the material supplier for efficiency versus temperature, and using the current array temperature calculated by SINDA. The incident power times the efficiency of the array material then gives the total instantaneous power generated by the solar array. Since there were several arrays on the rover, it was necessary to calculate the temperature and power generation of each, and sum them. An example plot of the instantaneous array power generated is shown in Figure 13. The code used to perform the calculations is shown in Table 2.

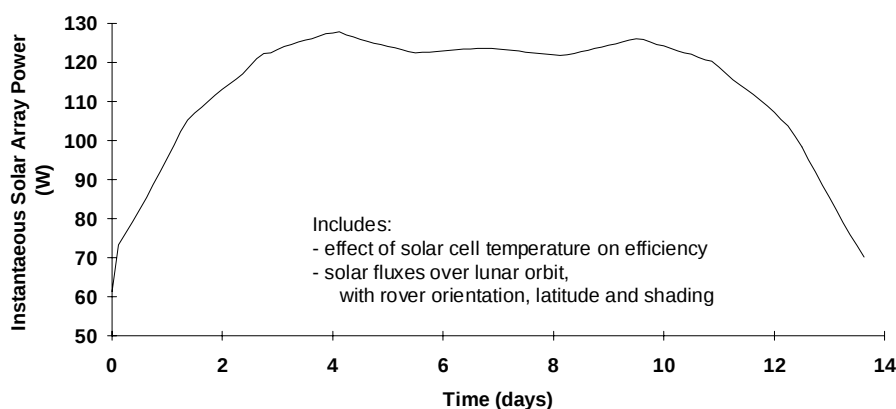


Figure 13. Solar Array Power Generation over Lunar Day for 75 degree Latitude

Table 2. Solar Array Power Calculations in SINDA Logic

```

HEADER ARRAY DATA, ROVER
C    TEMPERATURE DEPENDENCE OF SOLAR ARRAY POWER GENERATION
C    IN DEGREES C AND % (FRACTION) EFFICIENCY
      200 = 28., 0.18, 120., 0.143
...
HEADER OPERATIONS DATA
BUILD LUNAR, ROVER
C
C    OUTPUT FILE FOR SOLAR PANEL POWER GENERATION
F    OPEN (UNIT=27, STATUS='UNKNOWN', FILE='../rover/solar.pl', RECL=400)
C    PRINT POWER LABELS TO PLOT FILE
      WRITE (27,22) 'TIME', '301 W', '401 W',..., '2501 W', 'TOT W', 'W/ RAD', 'CUM. W/R'
22    FORMAT(15(A8,1H,),A9)
C
      WTEST = 0.                                $ Zero out total power numbers
...solution execution
      WRITE (27,78) WTEST                        $ Write total generated power at end of file
78    FORMAT ('TOTAL POWER AVAILABLE IS ',F10.1, ' WATT-HRS')

```

Table 2. Solar Array Power Calculations (con't)

HEADER OUTPUT CALLS,ROVER		
C		
C	CALCULATE POWER GENERATION IN SOLAR ARRAYS	
C	Qgen = Qin * 80% area / alpha	Q in already in W
C	Qreal = Qgen * % EFFICIENCY	
C		
	XK301 = Q301 * 0.80 / 0.88	\$ Power under perfect conditions
	CALL D1D1WM (T301, A200, 1., ETEST)	\$ Performance factor (-%/C)
	XK301 = XK301 * ETEST	\$ Actual power generated
C		
	XK401 = Q401 * 0.80 / 0.88	\$ Repeat for each array
	CALL D1D1WM (T401, A200, 1., ETEST)	
	XK401 = XK401 * ETEST	
...		
C	CALCULATE TOTAL POWER AVAILABLE	
	ATEST = XK301 + XK401 + XK501 + XK2301 + XK2401 + XK2501	
	WTEST = OUTPUT * ATEST + WTEST	\$ Total watt hours
C		
C	PRINT POWERS TO FILE	
	WRITE (27,25) TIMEN, XK301, XK401, ..., XK2501, ATEST, BTEST, WTEST	
25	FORMAT (15(F8.2,1H.),2(F14.3,1H.),3(F9.3,1H.))	

The power generation over time can be used to determine total energy available as well as charge of the on-board battery. The total energy available was calculated for different positions and orientations of the rover, to determine the effectiveness of the rover at different lunar positions. This information was used in planning nominal traverses for the rover.

THERMAL ANIMATION

Structural analysts commonly use animation in their presentation of results. Animation of mode shapes or predicted deflection patterns is a vivid method of capturing and conveying all the necessary information. This is done less often with thermal analysis, with the result that many viewers have a less concrete idea of the physical progression of temperatures or heat flows. A visual animation of the thermal map, in color, gives an effective representation of the physical transfer of heat.

Animation of transient thermal results, in combination with an integrated structural-thermal model, is a useful tool that has been utilized through PATRAN and its connection with SINDA. The temperatures of a part are mapped onto the geometry using a color scale. Color maps are generated for several sequential time steps, and the mappings are viewed in a sequence that is run repeatedly on the screen. The progression of temperatures along the part as a function of time is observed as an animated color thermal map. This function is valuable when evaluating the driving force behind a given reaction, and can also give an audience a much clearer understanding of the processes involved in a complex reaction. Cases can be recorded on video tape and used to demonstrate results to a larger audience. This function is also quite valuable to the analyst, as it provides a method for debugging the model and perhaps finding errors that would be time-consuming and tedious to find in any other way.

The specific method for performing this animation is to run SINDA with thermal output at all desired time steps. A virtual temperature (VTE) file must still exist from the PATSIN translation for the SINPAT translator to use in calculating nodal temperatures from element temperatures. Once SINPAT has created the nodal results files, the easiest way to set up an animation is to set up a PATRAN session file

that reads in all the frames. This avoids manual keying of three input lines per frame. The session file sets up the number of frames and the spectrum to be used. For each data frame, RUN, CONTOUR and RUN, HIDE commands are performed. The last line for the last frame must be typed in manually. After the last line is entered, the animation will begin running on the screen. The animation characteristics may be altered in real time using the animation menu. On 3-D workstations the part can be rotated on the screen during animation, so that thermal progressions on all sides of the part may be viewed.

CONCLUSIONS

The innovations that have been used here are useful to reduce modeling time and produce more accurate results. Model integration using a solid modeling package allows direct transfer of information between not only analysts, but designers as well. The technique of using the transient derivative for model reduction and correlation is beneficial in reducing the large solid-model-derived thermal analysis models, and in many other areas such as correlation to test data. The logic used in SINDA and TRASYS, while not unique, is a good example of the wide variety of output that results from the flexibility of incorporating user logic. Finally, the animation of thermal analysis results is a valuable tool for the analyst, and for aiding understanding when results are presented to a wider audience.

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